DETERMINATION OF LIQUEFACTION TRIGERRING FROM CPT

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ABSTRACT

The current state of the practice for evaluating liquefaction triggering is to calculate the cyclic stress ratio and the cyclic resistance ratio from correlations with either the standard penetration, cone penetration, shear wave, or Becker penetration field tests. Determination of the amount of lateral spreading that occurs is based on empirical correlations with observed field data. This paper reports the results of a research study to investigate the effect of liquefaction triggering with field data, namely the cone penetrometer test. This research involved centrifuge testing utilizing a miniature cone penetrometer system suitable for testing in-flight.

INTRODUCTION

Liquefaction of loose, water-saturated sands and other granular soils due to earthquake shaking is a major cause of damage to and destruction of constructed facilities. A 2-year research effort focusing on evaluation of liquefaction triggering (H_l), using the in situ static cone penetration testing (CPT) technique has been conducted at Rensselaer Polytechnic Institute (RPI), Troy, NY. In this investigation, liquefaction triggering measurements are directly correlated with the CPT in centrifuge model tests for various sand relative densities. These correlations, after proper verification against the available empirical and case history information related to both CPT and H_l in the field provide the basis for CPT-based charts to predict H_l in the field for given ground slope, soil conditions, and strong motion input.

This research employs physical prototype modeling using the centrifuge facilities at RPI and the development of a miniature CPT and containers appropriate for centrifuge testing. Several investigators have also shown promising results of modeling the CPT in sand in the centrifuge, with results reported by [Phillips and Valsangkar (1987), Corte et al. (1991), and Renzi et al. (1994)]. The results reported by Corte, and Renzi have also shown that a CPT profile conducted in the centrifuge can be used to predict tip

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resistance, q_c, in the field. Extensive work at RPI using a laminar box container inclined to the horizontal and shaken at the base have demonstrated the usefulness of centrifuge simulation of the lateral spreading phenomenon [Dobry et al., 1995; Taboada, 1995].

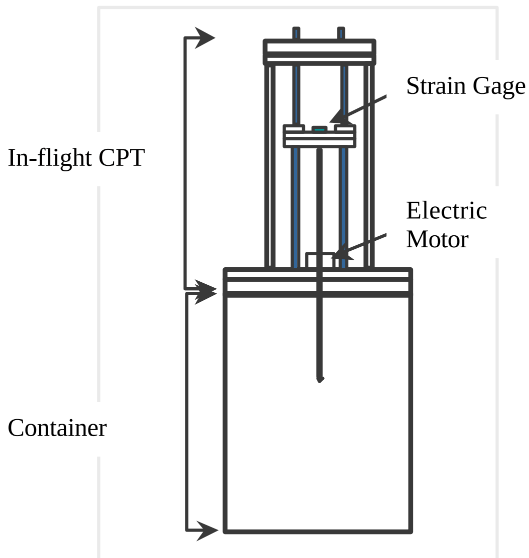

Figure 1. Schematic of In-flight CPT

DEVELOPMENT OF MINIATURE CPT SYSTEM

The system consists of a miniature CPT appropriate for testing in the centrifuge, with three miniature cones used in conjunction with the soil model container. The in-flight CPT (Fig. 1) is an electric chain driven system capable of penetrating into the soil model a distance of 1 m. The soil model container is cylindrical with a diameter of 50 cm and height in excess of 1 m. It is possible to model a soil deposit with a maximum field thickness of approximately 20 m. The miniature cones have diameters of 4, 8, and 12 mm, respectively. The use of three different cones was planned such that varying centrifugal accelerations could be tested while still maintaining the proper scaling relationship with the standard field CPT. That is, the 4 mm cone is being used at a centrifuge acceleration of 9g, the 8 mm cone at 4.5g, and the 12 mm cone at 3g, with all of them modeling the prototype CPT in the field at 1g having the standard diameter of

36 mm. In this way, each one of the cones serves as a ‘model of the models’ for the others, thus increasing the confidence of the results.

Container size and boundary conditions can affect CPT measurements. Several researchers [Parkin and Lunne, 1982, Renzi et al., 1994] have investigated the influence of boundary conditions on CPT data and have established a diameter ratio, R_d, defined as the ratio of the chamber diameter to cone diameter. These results indicate that the side boundary effects depend on the relative density of the sand. For loose sand with relative density on the order of 30%, the side boundary effects are negligible. For dense sand the chamber diameter must be at least 50 times the diameter of the cone to eliminate the effect of the side boundary on cone resistance. The results of work in a rigid walled chamber report diameter ratios of 28 to 39.7. These results indicate that for rigid walled chambers the side boundary effects are not significant when the diameter ratio is greater than 28. For the penetrometers and container developed at the RPI centrifuge, the minimum R_d values for the 4, 8 and 12 mm cones for pushes located at the center of the container are 125, 62.5, and 41.6 respectively. These values are larger than those reported in the literature and should assure that no boundary effects will occur for pushes made at the center of the container. In addition to the center of the container, pushes are also performed in the RPI investigation along two concentric circles, with the outer circle being 10 cm from the container’s edge. Pushes made close to the boundary would allow the failure mechanism to develop freely on the side of the probe away from the boundary but will be constrained on the side toward the boundary. In this case side-wall boundary effects are negligible even when the probe is located at a distance from the wall corresponding to $R_d = 5$. Using 10 cm as the distance to the wall gives R_d values of 25, 12.5, and 8.3 for the three cones used at RPI. As shown later by the preliminary results of in-flight cone penetration at RPI, these cone diameters and push locations showed no effect from the side-wall boundaries, as expected.

With respect to the bottom boundary effect, [Phillips and Valsangkar (1987)] reported that for a 10 mm cone, the bottom boundary effects are seen starting at a vertical distance of 10 to 12 cone diameters. In the case of the cones used in this experiment, the expected distance of bottom influence would be 48 mm for the 4 mm cone, 96 mm for the 8 mm cone, and 144 mm for the 12 mm cone. The tests at RPI reveal a bottom influence at vertical distances from the bottom consistent with these and others reported in the literature.

The prototype standard penetration rate for the CPT in the field is 2 cm/sec; for the in-flight tests being conducted at the RPI centrifuge the model penetration rate is 1 mm/sec. [Phillips and Valsangkar (1987), and Corte et al., (1991)] reported results of centrifuge tests in sand performed at penetration rates of 0.5-10 mm/sec with no noticeable difference in results. The penetration test appears to be a drained event in saturated sand. The rate of 1 mm/sec for the tests being conducted at RPI is believed to be consistent with prototype measurements, and also to be slow enough so as to assure drained conditions when a saturated sand model is tested.

The soil selected for these experiments is Nevada sand, having geotechnical properties as previously measured by [Arulmoli et al. (1992)]. This is the same sand that will be used for the lateral spreading experiments in the laminar box. The specific gravity of Nevada sand was determined to be 2.67 and the maximum and minimum densities were found to be 17.33 kN/m^3 (minimum void ratio = 0.511) and 13.87 kN/m^3 (maximum void ratio = 0.887), respectively. The grain size ranges from 0.1 to 0.25 mm and the soil classifies as a fine sand. [Renzi et al., (1994)] reported that soil particle size does not affect the results for a ratio d_c / d_{50} in the range of 90 to 50, where d_c is the model cone diameter. For Nevada sand, d_{50} = 0.13 mm, which gives $d_{4mm} / d_{50} = 30.7$, $d_{8mm} / d_{50} = 61.5$, and $d_{12mm} / d_{50} = 92$. No grain size effects were observed in the data for the RPI cones, as indicated by the excellent 'model-of-the-model' comparisons with the other cones.

CPT CENTRIFUGE TESTS PERFORMED AND RESULTS

Centrifuge results reported in this paper are from in-flight CPT on several relative densities and dry and saturated Nevada sand models. The sand was placed dry using the sand raining technique. In-flight CPT tests were performed on five models with nine to twelve cone penetrometer probes per model. A typical model was tested with each of the three probes (4, 8, and 12 mm) and three to four tests per probe. The tests were conducted by starting at the lowest g level, 12 mm at 3g, and finishing at the highest g level, 4 mm at 9g. The models tested were as follows; D_r=75% dry, D_r=75% saturated, D_r=65% dry, D_r=45% dry and D_r=45% saturated. A typical set of results is shown in Fig. 2. The agreement is excellent, confirming the 'model of the models' concept, as well as the agreement between dry versus saturated models at the same effective vertical stress, σ'_{vo}. This agreement of q_c versus σ'_{vo} for dry versus saturated data, allows us to assume a fully submerged deposit to a depth of about 20 m, despite the fact that the q_c measurements in the fully saturated sand models reached only to about 10 m prototype. Utilizing the plots for the data collected from the three different relative densities (75%, 65%, and 45%), and correcting the data for overburden pressure allows the creation of a plot as shown in Fig. 3. The parameter q_{c1} depends on the relative density of the soil and from the in-flight CPT tests of this experiment, the values are as shown in Fig. 3. These values and trends with σ'_{vo} are in excellent agreement with those reported by [Robertson and Wride (1997) and Olsen (1994)].

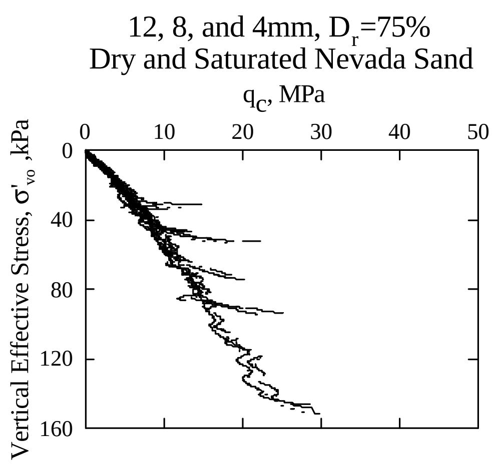

Figure 2. Results from D_r = 75% tests, dry and Saturated sand

LIQUEFACTION INDUCED LATERAL SPREADING TESTS PERFORMED AND RESULTS

A total of six tests were conducted to examine the effects of relative density, peak acceleration on the thickness of liquefied layer induced by liquefaction of a uniform deposit simulating a gentle, infinite slope. The models were constructed to the same relative densities as those used for the CPT models (45%, 65%, and 75%) and saturated. Peak accelerations were either 0.2 or 0.4g, thickness of deposit was 10 m. Figure 4 shows the inclined RPI laminar box container and typical model with instrumentation used to model lateral spreading in the centrifuge. The model is excited in-flight at the base of the container by a simulated earthquake acceleration time history. This earthquake excitation causes the soil to liquefy, and downslope permanent lateral displacements develop in the liquefied soil by the combined effect of static and dynamic shear stresses. Acceleration, pore pressure, and vertical and horizontal displacements measure the corresponding parameters during and after shaking. Accelerometers and pore pressure transducers in the model allow for the determination of the thickness of liquefied layer. Vertical displacement transformers measure the amount of settlement and horizontal displacement transformers measure the lateral spread and permit determination of shear strains in the deposit. From the tests conducted a plot such as shown in Fig. 5 can be constructed which plots relative density versus thickness of liquefied layer.

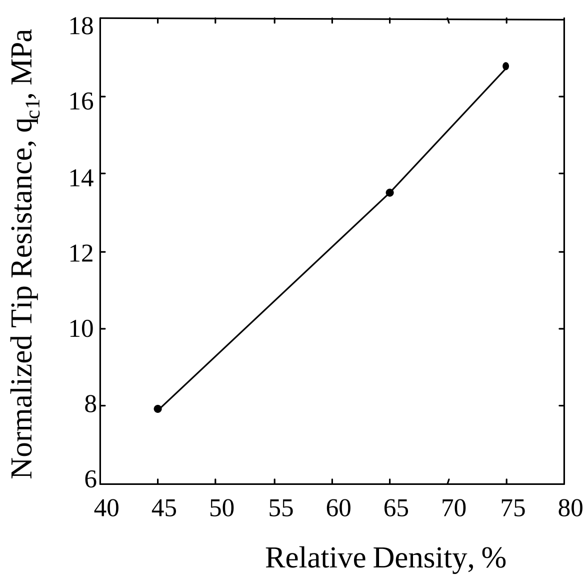

Figure 3. Normalized tip resistance versus relative density

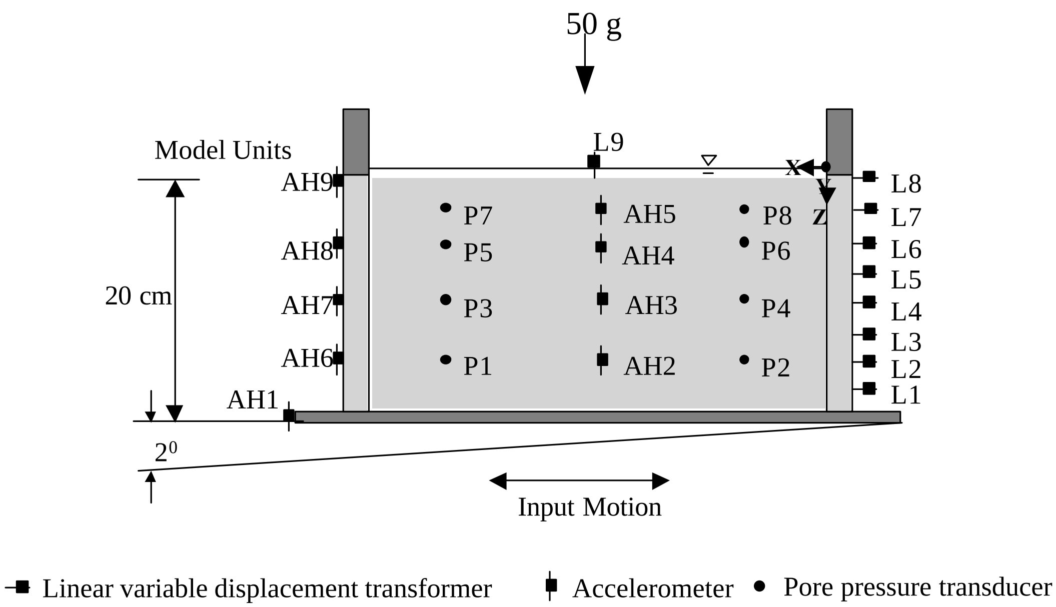

Figure 4. RPI laminar box and model setup for liquefaction tests

By combining the results shown in Fig. 3 with those shown in Fig. 5, a plot of corrected tip resistance versus thickness of liquefied layer can be made and shown in Fig. 6. This plot then is a prediction chart for determining the amount of lateral displacement based on the corrected tip resistance field data. However, the plot is for a specific type of deposit and level of shaking. The data represents a deposit of clean sand 10 m thick with a 5^0 slope, shaken with a peak acceleration of 0.2 or 0.4 g at a frequency of 2 Hz. Current work is focusing on generalizing these results to include variables such as different deposits, varying permeability, and varying earthquake shaking.

COMPARISON WITH FIELD DATA

[Robertson and Wride (1997)] gives the current methodology used to evaluate liquefaction triggering from cone penetration data. This technique is similar to the simplified procedure for the evaluation of liquefaction effects from the standard penetration test as proposed by [Seed et. al., (1983)]. A design earthquake motion is specified for the site in question and from this motion the cyclic stress ratio for the soil deposit is determined. From the cone penetration data [Robertson and Wride (1997)] provides a chart to determine the cyclic resistance ratio of the soil deposit. The thickness of liquefied layer or liquefaction triggering is then determined. His charts were developed from CPT data collected at sites that had experienced liquefaction. A comparison of the measured H_l from data collected in this research was made with the predicted H_l utilizing Robertson's technique and the two methods are discussed. All CPT data collected in this research was evaluated with the aforementioned technique, however only two comparisons are presented in this paper. Fig. 7a shows the D_r = 45% deposit with a design earthquake of M=7.5 and peak acceleration of 0.23g, and Fig. 7b the D_r = 75% deposit with M=7.5 and peak acceleration of 0.38g earthquake.

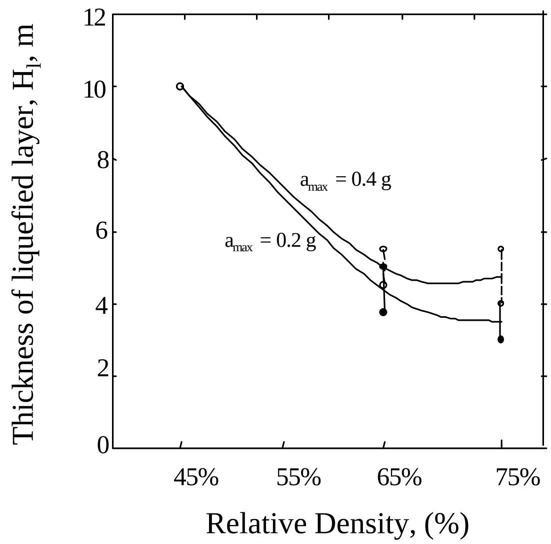

Figure 5. Thickness of liquefied layer versus relative density

Notice that comparison of the measured and predicted thickness of liquefied layer are in very good agreement. This provides for reliability of the measured CPT results and the thickness of liquefied layer, both obtained from scaled model testing in the centrifuge. Comparisons of the predicted and measured values for thickness of liquefied layer are given in Fig. 8. There is excellent agreement between the two values. Based on this comparison, the chart presented in Fig. 5 can be used, within the restrictions of the type of deposit, to determine the thickness of liquefied layer or liquefaction triggering for a similar deposit.

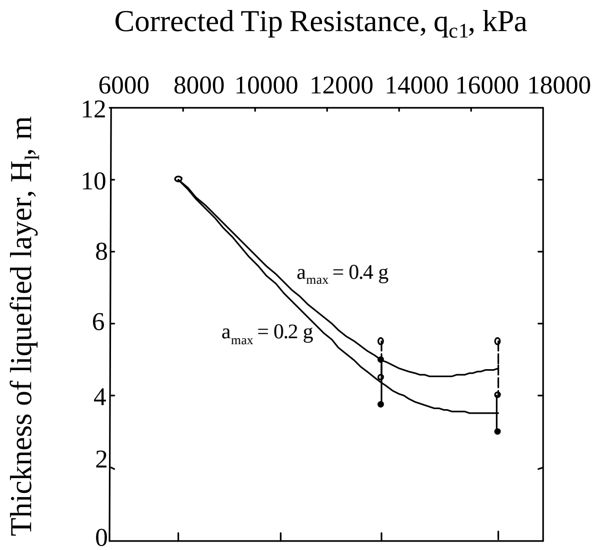

Figure 6. Thickness of liquefied layer versus corrected tip resistance

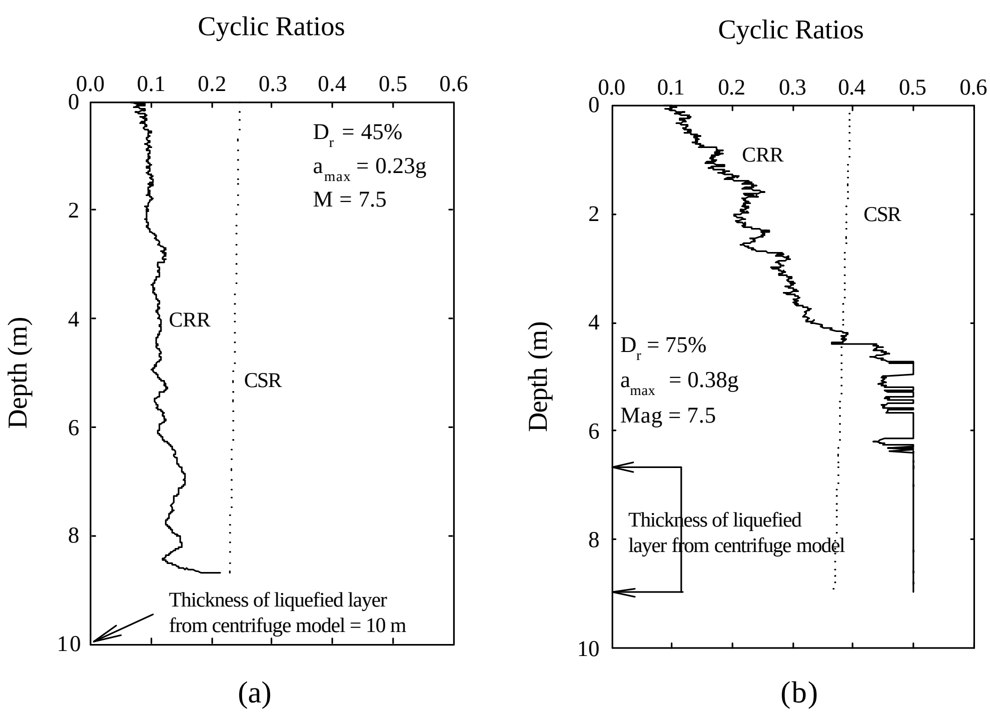

Figure 7. Depth versus cyclic ratios for D_r = 45% and 75% deposits

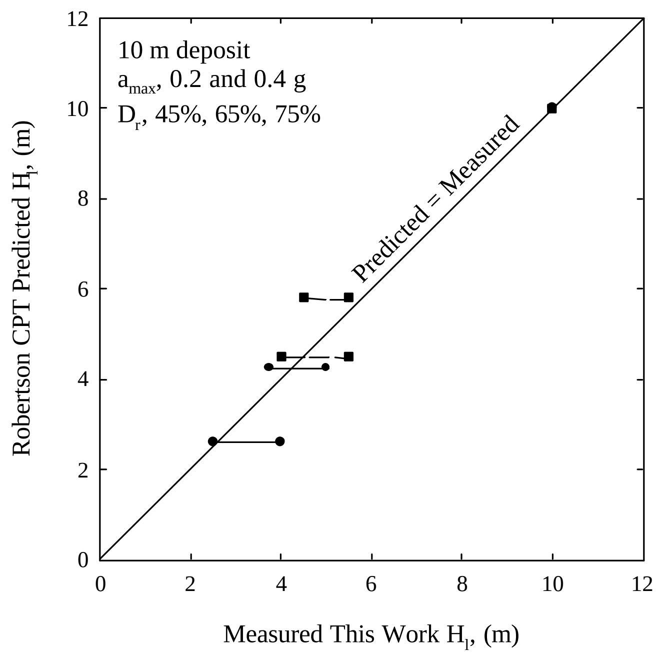

Figure 8. Predicted versus measured H_l

CONCLUSION

This paper has presented results from research aimed at improving the evaluation of earthquake induced liquefaction triggering. By incorporating results from centrifuge cone penetration testing and laminar box liquefaction testing, a methodology for the development of prediction charts has been established. Work is continuing to enhance these charts to incorporate more variables such as different deposit thickness, varying permeability, and varying earthquake shaking.

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